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Acoustic signature reduction, modulation and control

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In the present study the problem of the ship signature is dealt with considering the main perturbation sources that have a relevance on the propeller induced noise and vibrations. Specifically the following aspects that cause major effect on the hydroacoustic and propulsive performance of a marine propeller will be discussed: (i) the effect of the inflow, (ii) the contribution of the wake evolution and breakdown mechanisms, (iii) the propeller-rudder/propeller-strut interaction in conventional and podded propulsors. The results presented in the paper are part of research activities carried out by INSEAN, most of them supported by the Italian Navy. In this framework INSEAN has developed and implemented a number of advanced experimental and numerical tools, pioneering sometimes, which have aimed at probing into the complex problem of the hydrodynamic and hydroacoustic performance of a marine propeller.

Introduction

Nowadays, the problem of the hydrodynamic-induced noise and vibrations is an issue of relevance in both the navy and civil naval engineering in view of the need of reducing the vessel signature and the on-board comfort.
In this scenario, the perturbation induced by a marine propeller and its interaction with the hull and the ship appendages are the strongest noise sources on a ship typically in which the inflow quality on the propeller, the dynamic of the propeller tip and hub vortices, the mechanisms of the propeller wake instability and breakdown represent key aspects towards which concentrate the efforts for the performance improvement and the signature reduction.
From the research side, the problem of reducing propeller induced noise and vibrations has implied a rising interest on detailed investigation techniques of the propeller flow field to be used for both new design approaches as well as for the analysis of the propulsive, hydro-acoustic and structural performances.

In this framework, the Italian Ship Model Basin (INSEAN) is active through a long term research program on marine propulsion. The basic objectives of the program are:

- improve the operational effectiveness of surface ships and submarines by devising methods to optimize propulsor, hull form, and structural arrangement for low noise and high efficiency over a broad range of operating conditions;
- understand the physics of hydrodynamic noise generation from propellers;
- develop theoretical and experimental tools for formulating noise reduction and performance improvement strategies.

The understanding of the mechanisms that influence the performance of a marine propeller has implied a rising interest into the development of advance investigation techniques such to represent the details of such a complex hydrodynamic and hydroacoustic problem with high levels of detail and accuracy. On the experimental side, the activity includes the development of advanced velocimetry techniques based on optical methodologies (e.g. 2D-2C PIV, Stereo-PIV, Defocusing PIV, high–speed PIV) to characterize the flow field, and of image processing tools to provide quantitative predictions of flow features such as the cavitation pattern or the blade tip vortex location.

The support of such advance experimental tools has provided considerable insights into the problem of the propeller induced noise and vibration mechanisms and has suggested guidelines for their modulation and reduction.

The main results of these activities are discussed in the paper. More specifically, the following aspects are tackled and described:

1. Effect of the inflow on the propeller hydroacoustic and propulsive performance. The non-uniformity of the onset flow on the propeller induces variable radial and angular fluid dynamic loads along the blade and, hence, a thrust and torque distribution which changes during the revolution (Felli and Di Felice, 2005). These changes lead to propeller-induced-vessel-vibrations, unsteady cavitation and noise generation. In addition the impact of the vortical structures shed from the hull and the ship appendages (e.g. bilge, sail and rudder vortices in a submarine, shaft brackets, anti-rolling devices) on the propeller may jeopardize the performance considerably besides emphasize the contribution at the blade harmonic in the spectrum, aspect this particularly critical for the ship identification. Therefore, the interaction between the propeller and its inflow is an important issue for the performance improvement and the signature reduction.
2. Propeller wake evolution and breakdown mechanisms. The tip vortex passage is the most important noise source in generating the hydrodynamic pressure field in the propeller flow within the slipstream contraction (Felli et al., 2006). In the transition wake the process of energy transfer from the blade to the shaft harmonic occurs with different mechanisms that depend on the blade number and is correlated to the mutual interaction between adjacent spirals of the wake (Widnall, 1972). In the far wake, the mechanism of wake instability produces an energy transfer from the blade to the shaft harmonic, that is correlated to the occurrence of a precession motion of the propeller streamtube around the spiral geometry of the destabilized hub vortex mainly (Di Felice et al., 2004; Felli et al., 2006);
3. Propeller-rudder/propeller-strut interaction. The propeller-rudder or the propeller-strut interaction in a conventional propeller-powered vessel or in a pulling type podded propulsor give an important contribution to the ship signature that is correlated to the impact and the deformation of the propeller vortex filaments, the unsteady and non-uniform inflow on the rudder/strut and the propeller induced cavitation mainly. The results of experimental activities on this topic (Felli et al., 2004; Felli et al. 2006a, Felli et al. 2006b) have shown evidence of these phenomena with detail and have given guidelines for the improvement of the rudder/strut installation and design.

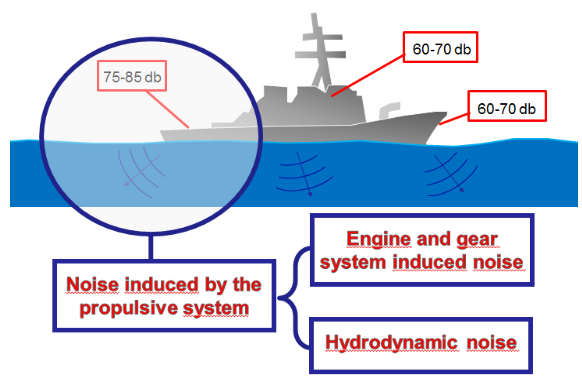

Figure 1. Noise sources in a ship

1. Effect of the inflow on the propeller hydroacoustic and propulsive performances

The accurate investigation and assessment of an installed propeller wake plays a fundamental role in the naval field where the propeller performances are dependent upon the upstream wake largely. Non-uniform inflow conditions induce variable radial and angular fluid dynamic loads along the blade actually and, hence, a thrust and torque distribution which changes during the revolution (Figure 2). These changes concern both intensity fluctuations of thrust and torque and periodic displacements of the thrust centroid on the side where the hydrodynamic load is larger.

The periodic variations of the hydrodynamic loads and, with them, of the intensity of the propeller vortical structures jeopardize the propeller performance and the ship signature causing the increase of the propeller-induced vessel vibrations and noise generation, the development of unsteady cavitation and the danger of structural damages due to fatigue stresses and erosion, sometimes.

As an example of the nature of the perturbation that the onset flow non-uniformity induces on the propeller wake figure 3 describes the distribution of the axial velocity and the turbulent kinetic energy for a twin screw fast ferry ship (Felli and Di Felice, 2005).

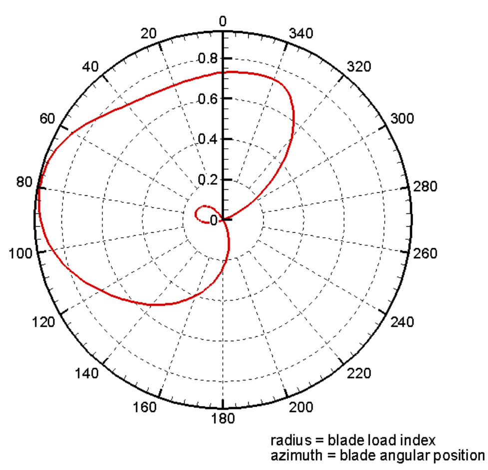

Figure 2. Azimuthal variation of the blade hydrodynamic load calculated on the basis of the tip vortex circulation and the blade load index. Note that the periodical variation of the blade hydrodynamic load results in periodical fluctuations of the propeller vortex intensity that are associated with the wake induced noise and vibrations phenomena.

The contour plots of Figure 3 documents the following typical features of an installed propeller wake: (i) the non-axisymmetric distribution of the velocity field (e.g. in the example of Figure 3 the induced velocities have a maximum on the inner half-plane where the inflow, upward direct as the consequence of the stern geometry, is counter-rotating as to the propeller); (ii) the perturbation of the shaft and the shaft-brackets (e.g. in the example of Figure 3 the perturbation of the vertical bracket, particularly strong because of the not good keying, is such to shake the propeller tip vortices locally causing a sensible increase of the induced noise and vibrations).

In some cases, typical of submarines (Figure 4), the propeller onset flow may be dominated by strong vortical structures shed by the sail (horse-shoe sail vortices), the hull (bilge vortices) and the rudders that impact on the blades and compromise the signature and the performances sensibly. The impact of the above vortical structures on the propeller gives a perturbation that recurs at each blade passage periodically, emphasizing the contribution at the blade harmonic in the spectrum. This aspect reveals particularly critical for the ship identification.

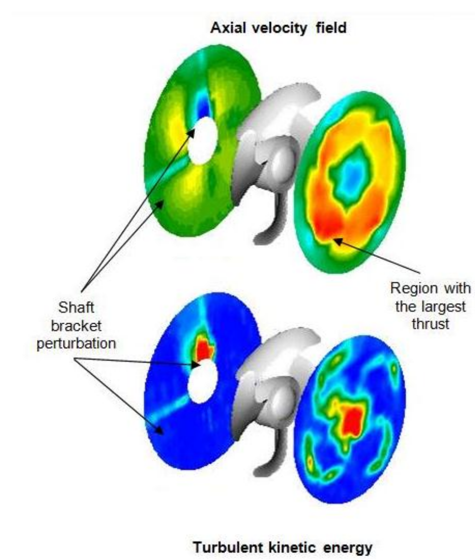

Figure 3. Axial velocity field and turbulent kinetic energy for a propeller blade operating in behind condition.

In these cases, the wake signature can be reduced optimizing the hull design in order to avoid the impact of the aforementioned vortical structures with the propeller as much as possible or introducing hydrodynamic devices, such as counter-vortex generators and deflectors, by which getting the propeller-vortex interaction weaker.
The support of advanced experimental techniques reveals particularly suitable for the propeller inflow improvement and for the performance improvement. In fact, a local survey of the flow field is such to provide a detailed diagnosis of a signature problem and might suggest possible solutions for its overcoming unlike global measurement techniques that reveal the occurrence of a problem only without giving useful information on its nature.

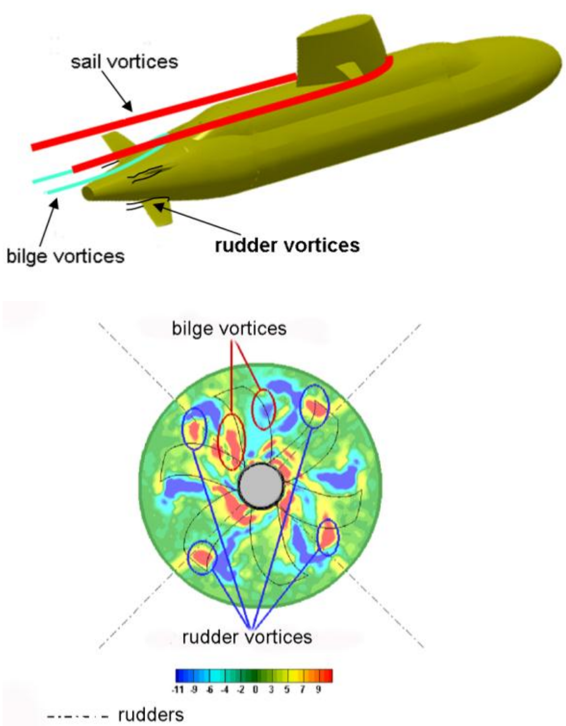

Figure 4. Sketch of the vortical structures that impact on a submarine propeller typically (top). Distribution of the vorticity field just behind the propeller trailing edge: note the interference between the propeller trailing wake and tip vortices with the vortical structures of the inflow (bottom).

Figure 5 shows a typical problem of cavitation induced by the inflow non-uniformity. More specifically the analysis concerns the case of a propeller installed behind a wake generator. The effect of the cavitation, estimated by the visualization of the cavitation pattern in combination with simultaneous measurements of the pressure fluctuations, appears as a sensible increase of the pressure fluctuations when the blades cross the wake of the generator (i.e. top vertical position) (see top-left of figure 4). In this position the width of the cavitation pattern, measured by an imaging processing technique based on the cross-correlation between a template image, (i.e. the blade viewed in non-cavitating conditions), and the image to analyse (see Pereira et al., 2004 for further details on the technique), undergoes a sensible increase as shown in the top-right of figure 5 clearly.

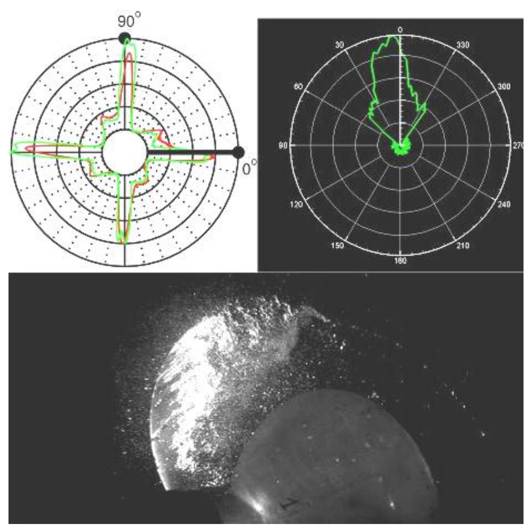

Figure 5.Propeller in behind condition: cavitation induced by the inflow non uniformity (bottom). Cavitation induced pressure field (top-left). Cavitation pattern width (top-right). (Pereira et al., 2004)

2. Isolated propeller signature

The mechanical energy that the propeller transfers to the vortical structures of the wake (i.e. tip and hub vortices, trailing wake) represents a potential that is converted into

structural, fluid-elastic and fluid-acoustic perturbations and, thus, has a direct impact on the signature. The nature and the mechanisms by which the aforesaid perturbations occur are correlated to the processes of evolution, instability and breakdown of vortical structures of the wake. For this reason, the analysis of the different contributions that influences the wake signature cannot be performed apart from a detailed knowledge of the mechanisms that guide the dynamic of the propeller wake structures. Following the classification proposed in literature (Stella et al., 2000), the evolution of the propeller wake develops along three main regions: the first, known as "near wake", featured by the process of development and roll up of the wake and culminating with the slipstream contraction; the second, known as "transition wake" where the propeller wake undergoes a process of gradual destabilization of the vortical structures; and a third zone, known as "far wake" or "ultimate wake", where the propeller wake definitely breaks down.
The width of each region depends on the propeller loading condition strictly: the larger the blade load, the faster the transition to the instability, the more contracted the wake evolution (Di Felice et al., 2004).

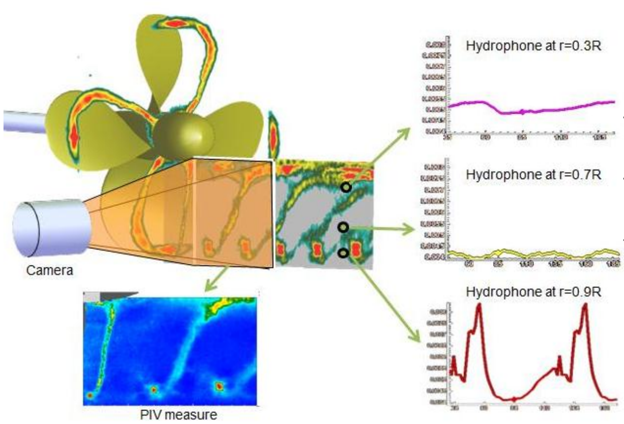

Figure 6. Correlation between velocity field, by PIV images, and pressure signal at θ=20°. The longitudinal station corresponds to x/R=1.0. Marks in the contour plot evidence the pressure probe positions.

The analysis of the phase-correlations between velocity and pressure signals reveals a suitable approach to identify the noise sources in the propeller wake and to qualify the nature of their perturbation. In this regard, Felli et al. (2006) measured the phase averaged velocity and pressure field in the wake of a four bladed propeller (Figure 6). The analysis, performed measuring the pressure field in four radial positions of the near wake (i.e. r=0.3R, r=0.7R, r=0.9R, r=1.2R) shows that the maximum values of the pressure fluctuations are correlated to the passage of the tip vortex. It follows that the tip vortex is the most important pressure fluctuation source in the near wake of a propeller whose spectrum is dominated by the contribution of the blade harmonic. Note that the pressure fluctuation peaks in the diagrams of Figure 6 are one order of magnitude larger at r/R=0.9 as to the other locations at r/R=0.3 and at r/R=0.7.
The amplitude of the pressure fluctuations reduces when increasing the advance coefficient (i.e. reducing the blade load) because of the reduced intensity of the tip vortex.
Further downstream, in the transition wake, the slipstream perturbation is involved in a multi-step process of energy transfer through which the energy flows from the blade to the shaft harmonic. This mechanism of energy transfer is correlated to the dynamic of the tip vortices and occurs with different features dependently on the blade number (i.e. number of spirals of the propeller wake).
In this regard, Felli et al. (2008) describes the following mechanisms featuring the evolution of the tip vortices in the transition wake of a two-, three- and four-bladed propellers (Figure 7):

- Two-bladed propeller. Propeller wake instability and breakdown occur several diameters downstream the propulsor (i.e. more than 17R at J=0.8). This is the consequence of the larger distance between consecutive filaments that delays the beginning of the stable-unstable transition. The mechanism of energy transfer occurs with a direct passage from the blade to the shaft harmonic and is correlated both to the joining mechanism between consecutive vortex filaments, that leads to a "period-doubling" in the PSD and a progressive reduction of their distance, and to the hub vortex inductance. The former prevails at the beginning of the transition wake, the latter becomes stronger and stronger far downstream, where the intensity of the tip vortices and, thus, their perturbation is very weak.

- Three-blade propeller. The direct energy transfer from the blade harmonic to the first and second shaft harmonics is associated with the alternate grouping among adjacent filaments and the inductance effect of the oscillating hub vortex. The analysis of the phase evolution of the velocity signal points out two main features: on the one hand, the traces of the three tip vortices tend to get closer and to group, on the other hand, two filaments in each group tend to attract each other and to couple with a "leapfrogging" mechanism (second blade harmonics). Further downstream, the second grouping (one-filament with one-filament-pair) and the hub vortex inductance result in a complete joining among the three vortex filaments that transfers energy from the second to the first shaft harmonic, definitely.

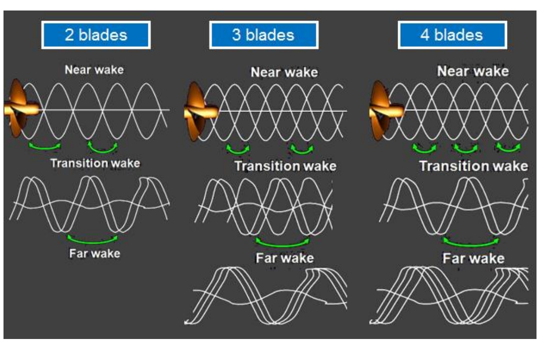

Figure 7. Propeller wake evolution mechanism for the two- (left), three- (mid) and four- (right) bladed propellers at J=0.45. Snapshots are spaced of $\Delta t=0.1 \cdot T$.

- Four-blade propeller. The aforementioned cascade mechanism of energy transfer is the result of double "period halving" process that accomplishes the grouping of two vortex filaments and two-filament-pairs in a filament-pair and a group of four-filaments, respectively.

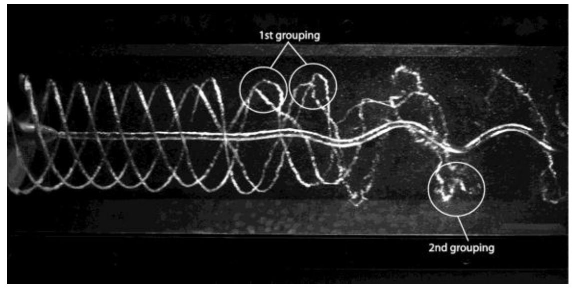

Figure 8. Filament grouping for the case of a two-bladed-propeller.

The afore-described mechanisms of energy transfer to the shaft harmonic that features the dynamic of the tip vortices are gained by a further phenomenon in which the propeller streamtube starts to describe a precession motion around the hub vortex (Felli et al., 2006).

3. Propeller-rudder/propeller-strut interaction

The knowledge of the interaction effects between the propeller and the rudder/strut is nowadays a focal aspect for the improvement of the ship performance and the reduction of the wake signature. Actually, the present trend to increase the ship speed and the propeller thrust consequently has made the problem of the mutual-interaction between the propeller and the rudder particularly critical, because of the many spin-offs on the hydroacoustic, structural and propulsive performance of the ship.

In conventional propeller powered vessels, propeller and rudder are considered as a propulsion unit in which the former is an active device that generates the thrust to keep the ship on speed and the latter a control surface that produces the transverse force to keep the ship on course. The rudder's effectiveness in producing a turning moment is proportional to its lift force (side force), which depends on the dynamic pressure of the incoming flow.

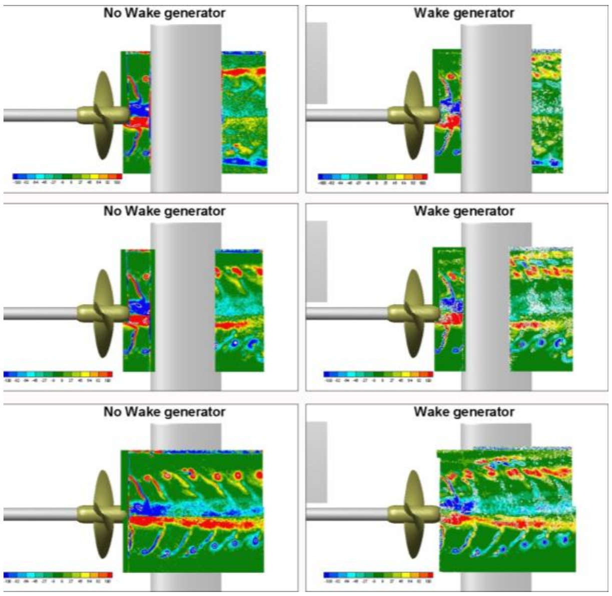

Figure 9. PIV measurements along the vertical-chordwise planes at y=0 (top), y=0.05·c (mid) and y= y=0.11·c (bottom) (c=180 mm is the rudder chord). Y-vorticity at the propeller angle θ=0°. Lines represent the iso levels of the complex eigenvalue of the velocity gradient. Configuration with the propeller in open water (left) and behind the wake generator (right)

That is why rudders are placed behind the propeller slipstream mostly, where the flow is accelerated. In spite of the general improvement in the ship manoeuvrability and control due to the better hydrodynamic efficiency, the installation of the rudder behind the propulsor leads to a number of side effects, linked to the unsteady nature of the propeller slipstream and the complex interaction with its vortical structures mainly. More specifically:

- The unsteady and rotating slipstream of the propeller makes the rudder working at incidence even if it is made of symmetrical profiles and it is operating in cruise trim condition. The local incidence at the rudder leading edge changes along the appendage span periodically and, in the case of highly loaded propeller, can be such as to cause flow separation and an efficiency loss in manoeuvring.
- The complex vortical flow induced by the propeller on the rudder can expose to the danger of cavitation (sheet cavitation, gap cavitation, vortex cavitation) that compromises the hydrodynamic and the hydroacoustic performances of the ship, with an overall worsening of the comfort on-board comfort and the wake signature.
- The interaction of the propeller vortices with the rudder causes a complex stress at the blade frequency that causes noise, vibrations and fatigue stresses. Such an effect is amplified for highly loaded propellers due to the bigger strength of the vortical structures.

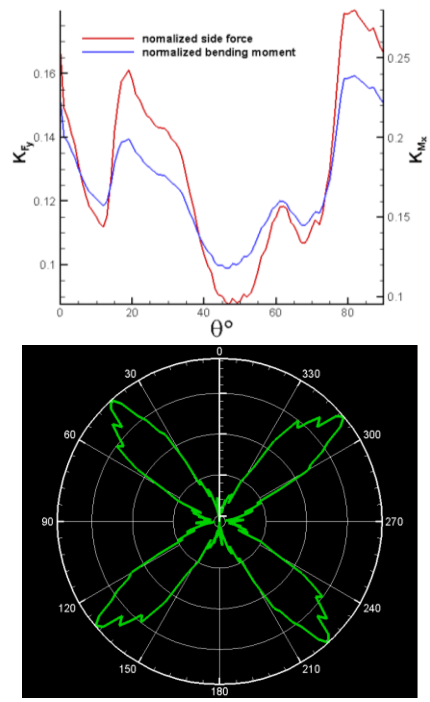

Figure 10. Angular evolution of the dimensionless side-force and the bending moment (top) and of the pressure fluctuations (bottom)

The accurate analysis of the flow around a rudder is a challenging task when the influence of the propeller is important. Actually, the need for an improvement in the detailed aspects of the rudder performance improvement has implied a rising interest in detailed

experimental analysis, to be used for both new design approaches (as in the case of the twisted rudder (Shen et al., 1997b)) and to get a better insight into the complex mechanism of interaction with the propeller slipstream.
Some examples of experimental investigations on the propeller-rudder interaction are reported hereinafter.

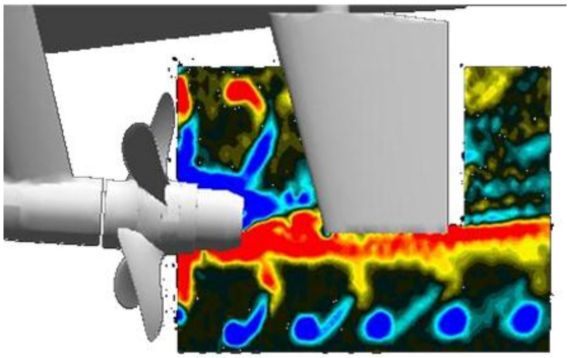

Figure 11. Phase locked evolution of the vorticity field. Note the decay of the vorticity intensity behind the rudder: this energy is transferred from the flow to the rudder and converted in noise and vibrations mostly.

The distribution of the phase averaged vorticity field around a rudder operating in the race of an open water and an installed propeller is reported in figure 9 (Felli et al., 2010). The contour plots of the mean and turbulent velocity field and the vorticity field show evidence of the strong perturbation induced by the rudder. In this regard, the phase averaged distribution of the side force, the bending moment and the pressure fluctuations in figure 10 highlight the unsteady nature of the rudder perturbation.
The effect of the energy transfer from the flow to the rudder is documented in Figure 11: the intensity of the tip vortices reduces significantly after their interaction with the rudder. This energy is mostly converted into vibrations, fatigue stress and noise.
Close to the rudder surface blade tip vortex slows down more and more and starts to deform itself while rolls up around the appendage. Suddenly, the vortex trace appears very stretched on the other surface of the rudder where is strongly shaken because the interaction with the rudder tip vortex. The complex deformation that the tip vortex undergoes periodically when it crosses the wake of the rudder is coupled with a sensible increase of the turbulent kinetic energy locally that is the source of noise and vibrations.
The phase locked evolution of the shaft and blade harmonics is described in the contour plots of Figure 12, for three different positions of the propeller.
During a propeller rotation, the mean values of the shaft harmonic exhibit the larger fluctuations in the rotation lower side of the propeller and correspondingly to the hub vortex region.
A different behavior is instead observed in the contour plots of the blade harmonic that fluctuate periodically attaining the maximum values of the peak-to-peak distance in correspondence of the tip vortex region.

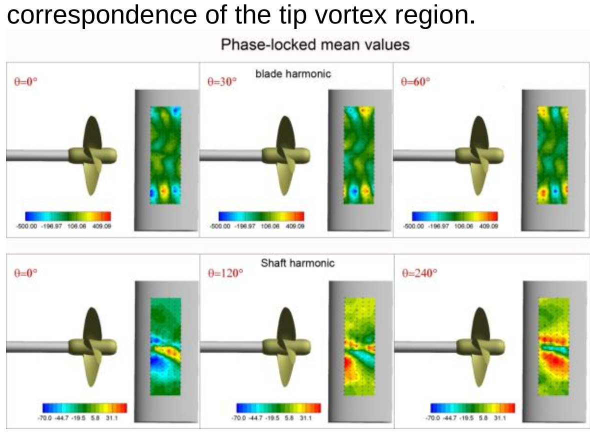

Figure 12. Pressure measurements on the rudder. Evolution of the phase averaged pressure signal reconstructed using only the blade harmonic (top) and the shaft harmonic (bottom).

Conclusions

In the present paper, the problem of the propeller signature is addressed by the analysis of the some typical perturbation sources that have an effect on the hydrodynamic and hydroacoustic performance of a propeller. More specifically three cases of relevance in the identification of the contributions that affect the signature of a propeller are considered: the problem of a propeller operating in behind condition, the perturbation sources in the wake of an isolated propeller and the propeller-rudder interaction. Some examples describing the results of experimental analysis performed by the Cavitation and Propulsion Laboratory of INSEAN are illustrated.

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